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Variation of lubrication condition during sheet hydroforming

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Abstract

A variation of lubrication condition on die surface during square cup sheet hydroforming was investigated experimentally. The lubrication condition on the die surface became worse in the late stage of the process. This would be because the thickening at the sheet edge in the lateral directions became larger than the film thickness of pressure medium; thus the contact area between the sheet and the die surface increased. To further investigate the difference in the lubrication condition depending on a position on the die surface, some holes were made on the die surface to let the pressure medium flow out through the holes during the process. The lubrication condition became further worse when the pressure medium was released through the holes in the diagonal directions, while remained almost unchanged when released in the lateral directions. This difference might be because the lubrication condition in the lateral directions became worse owing to the thickening in either case, whereas that in the diagonal directions became worse only when the pressure medium was released in the diagonal directions. The above results showed that the lubrication condition was different depending on the position on the die surface.

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Keywords: Sheet hydroforming ; Deep-drawing ; Fluid-lubrication effect ; Outflow of pressure medium ; Effective punch force

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1. Introduction

Sheet hydroforming is a deep-drawing process in which hydraulic pressure is used instead of a female die. In sheet hydroforming, the hydraulic pressure gives rise to the following three main features: the friction-increasing effect, the pre-bulging effect, and the fluid-lubrication effect (Kasuga and Nozaki, 1958a, 1958b; Nakamura & Nakagawa, 1984; Amino et al., 1990; Hama et al., 2009a). Because of these features, sheet hydroforming offers many advantages such as an improvement in dimensional accuracy, a reduction in tooling costs, and an increase in the limiting drawing ratio. Nowadays, it is employed in various industries, including the automobile, aerospace, and consumer electronics industries (Amino et al., 1990; Nakagawa et al., 1997).

Because it is quite difficult to determine forming conditions appropriately in sheet hydroforming, a preliminary investigation on the formability using the finite element method is required. For this purpose, there are several simulation programs that can be used for the simulation of sheet hydroforming processes (Lang et al., 2004; Önder and Tekkaya, 2008) including the one developed by the authors (Hama et al., 2007). On the other hand, there are still some technical problems in the simulation that should be solved. One of them is the modelling of the change in the lubrication condition owing to the outflow of the hydraulic pressure medium during sheet hydroforming. When the hydraulic pressure in the chamber reaches a certain magnitude, the pressure medium starts flowing out through a gap between the sheet and the die. The outflow of the pressure medium results in the fluid-lubrication effect between the sheet and the die, thus allowing a large draw-in. Therefore, to simulate accurately the sheet hydroforming process, the outflow of the pressure medium should be taken into account in the simulation. However, because the outflow characteristics of the pressure medium are not understood well, it is still difficult to model appropriately the outflow of the pressure medium and eventually the fluid-lubrication effect.

To solve this problem, the authors have been studying to understand the outflow characteristics of the pressure medium and to model the fluid-lubrication effect. In our previous studies, we examined experimentally the outflow of the pressure medium and its effect on the fluid-lubrication effect during a square-cup sheet hydroforming process (Hama et al., 2009a, 2009b, 2012). These studies clarified the variation of the hydraulic pressure in the flange area during the process and the influence of the outflow volume of the pressure medium on the fluid-lubrication effect.

In the present study, to further understand the lubrication characteristics during the square-cup sheet hydroforming process, the change in the lubrication condition during the sheet hydroforming process, in particular the variation in the fluid-lubrication effect, is examined experimentally.

2. Experimental procedures

2.1. Experimental setup

Figs. 1 and 2 show schematic diagrams of the experimental setup and the die surface used in this study. The experimental setup is the same as that used in our previous studies (Hama et al., 2009b, 2012). A cross-sectional shape of the punch was a square whose dimensions were 35 mm × 35 mm with a corner radius of 10 mm. The punch shoulder radius was 5 mm. In this paper, the directions along lines OA and OB (Fig. 2) are hereafter

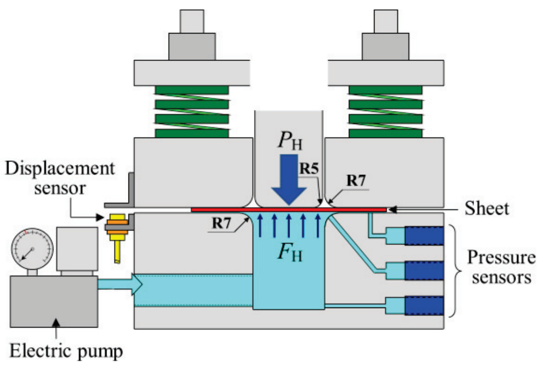

Fig. 1. Schematic diagram of experimental setup used in square-cup sheet hydroforming.

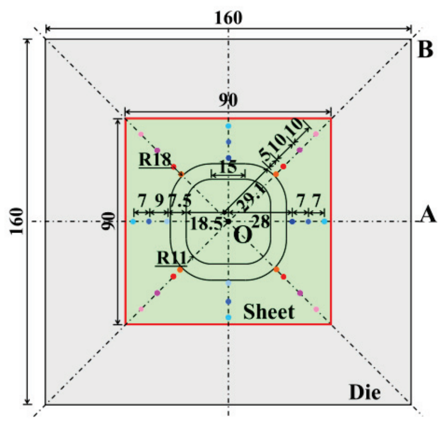

Fig. 2. Geometry of die surface.

termed OA and OB directions, respectively. Twenty-two holes were bored in the flange area through the sidewalls of the die. Pressure sensors (Kyowa Electronic Instruments, the PGL-A series) were used to measure hydraulic pressures and were mounted at the end of each hole as shown in Fig. 1. The blank holding force was maintained using springs with a spring constant of 943 N/mm and was set to 15 kN. Mineral hydraulic oil was used as the pressure medium as well as for lubrication. The sheet was drawn at a constant punch speed of 1.0 mm/s until a punch stroke reached 30 mm. At the same time, the electric pump was used to pressurize the pressure medium in the chamber from the beginning of the process in order to let the pressure medium start flowing out in the early stage of the process.

Displacement sensors (Keyence, model EX-110V) were used to measure the variation in the gap between the blank holder and the die during the process (hereafter simply termed the gap). It should be noted that the gap before the process began was set to zero and the variation in the gap from the beginning was measured. Variations in the hydraulic pressure, the gap, and the punch force were recorded every 5 ms throughout the process. Mild steel was used as the sheet material and its mechanical properties are shown in Table 1. The dimensions of the square sheet blank were 90 mm × 90 mm with a thickness of 0.75 mm.

Table 1. Mechanical properties of specimen.*

E /GPa	σ_y /MPa	F /MPa	n	ε_0	r - value
194.4	157	503	0.22	0.005	1.7

*E is Young's modulus, σ_y is the yield stress, and r is the Lankford value. The true stress-true plastic strain curve can be approximated with Swift's law $\bar{\sigma} = F(\varepsilon_0 + \bar{\varepsilon}^p)^n$ in the range of $0.1 \le \bar{\varepsilon}^p \le 0.2$

2.2. Forming condition

To investigate the difference in the fluid-lubrication effect depending on the position of the die surface, the lubrication condition on the die surface was changed artificially as follows. Originally the pressure sensors were mounted at the end of the holes as mentioned above. In the present study, some sensors were purposely detached from the holes to let the pressure medium flow out through the holes. Owing to the outflow of the pressure medium through the holes, it was expected that the lubrication condition in areas where the pressure medium was released would become worse. The following two conditions were tested: the conditions in which the pressure sensors were detached in OA and OB directions, respectively. Hereafter these conditions are termed OA-opened condition and OB-opened condition, respectively.

2.3. Effective punch force

In the present study, the so-called effective punch force (Kasuga & Nozaki, 1958a) was used to compare the formability among the conditions. The effective punch force P_E is given as follows

$$P_E = P_H - F_H \,, \tag{1}$$

where P_H is the punch force during sheet hydroforming, and F_H is the upward force owing to the hydraulic pressure in the chamber. Fig. 1 schematically shows these forces acting on the sheet. F_H can be calculated by integrating the hydraulic pressure with respect to the projected area of the punch and the sheet thickness. The present authors (Hama et al., 2012) showed that the difference in the effective punch force P_E among the forming conditions could represent the difference of the friction force between the die and the sheet depending on the forming conditions.

3. Results and discussion

3.1. Experimental results

Fig. 3 shows the variations of the effective punch force as a function of the punch stroke obtained for OA-opened condition, OB-opened condition, and original condition. It should be noted that the experiment was carried out for at least three times each condition to confirm the reproducibility. The punch force for OA-opened condition is in very good agreement with that of original condition, and the sheet could be drawn to a punch stroke of 30 mm in these conditions. In the case of OB-opened condition, on the other hand, although the punch force is almost the same with the other conditions until a punch stroke of about 18 mm, it becomes larger than that of the other two conditions thereafter. Moreover, the sheet fractured before a punch stroke reached 30 mm in OB-opened condition.

Fig. 4 shows the thickness strain distributions in OA and OB directions at punch strokes of 10 mm and 19 mm for OA-opened condition and OB-opened condition. The thickness strain was measured for at least two samples each condition and we confirmed the reproducibility. A large thinning is observed around the punch shoulder. Especially, in the case of OB-opened condition, a local thinning is developed at a punch stroke of 19 mm, which eventually leads to the fracture. These results indicate that the lubrication condition became worse when the pressure medium was released through the holes in the OB directions. On the other hand, a large thickening is observed at the sheet edge in OA direction at a punch stroke of 19 mm in either case.

3.2. Discussion

The lubrication condition would have a strong correlation with the gap because the outflow of the pressure

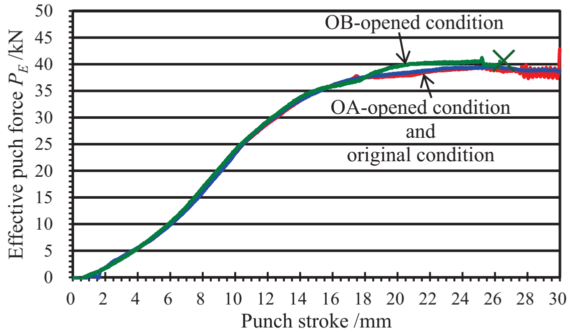

Fig. 3. Variations of effective punch force.

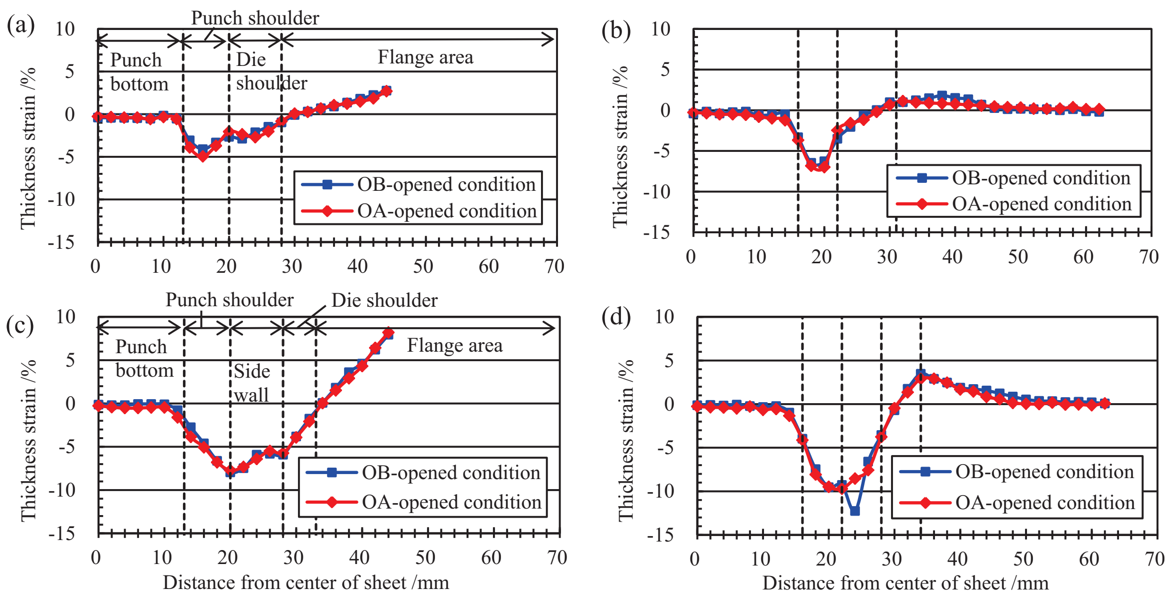

Fig. 4. Thickness strain distributions. The results are at punch strokes of (a) 10mm in OA direction, (b) 10mm in OB direction, (c) 19mm in OA direction, and (d) 19mm in OB direction.

medium should affect the change in the gap during the process. On the other hand, the thickening at the sheet edge (Fig. 4 (c)) may also affect the change in the gap. To examine the net effect of the outflow of the pressure medium on the gap, the following experiment was carried out. The sheet was first drawn up to a prescribed punch stroke. The punch and the pump were then terminated and the change in the gap between before and after the pump was terminated was examined. Hereafter the prescribed punch stroke is termed a terminated punch stroke. Fig. 5 shows the cross-sectional diagrams along OA direction during the process before and after a terminated punch stroke. Because the outflow of the pressure medium stops after the pump is terminated, it is presumed that the gap after the pump is terminated is mainly determined by the sheet thickness (Fig. 5 (b)) and that the gap change between before and after the terminated punch stroke (hereafter simply called the gap change), Δg, represents the film thickness of the pressure medium at the thickening region. As an example, Fig. 6 shows the variation of the gap during OB-opened condition with the terminated punch stroke of 15mm. The gap decreases from about 20 μm to about 15 μm when the pump is terminated, indicating that the film thickness at the thickening region is about 5 μm.

Fig. 7 shows the relationships between the gap change Δg and the terminated punch stroke obtained for OB-opened condition and OA-opened condition. In the case of OB-opened condition, the gap change increases as the terminated punch stroke increases from 5 mm to 10 mm. This indicates that the amount of gap by which the pressure medium lifts up increases. This result may be because the excluded volume in the chamber increases at this stage and the thickening at the sheet edge is still small (Fig. 4 (a)). Thereafter the gap change decreases as the terminated punch stroke increases. This result may be due to the fact that the thickness at the sheet edge in OA direction becomes large; thus the gap starts being supported by the sheet edge in OA direction at this stage. At the terminated punch strokes larger than 19 mm, the gap change is negligibly small. This shows that the pressure medium hardly lifts up the sheet; thus the gap is determined mainly by the sheet thickness. Clearly the thickening at the sheet edge is emphasized at a punch stroke of 19 mm (Fig. 4 (c)). The above results indicate that the gap is determined mainly by the film thickness of the pressure medium at the thickening region up to a punch stroke of about 10 mm, whereas by the thickness of the sheet at punch strokes larger than about 19 mm. The variations of the gap change obtained for OB-opened condition and OA-opened condition are in agreement with each other.

From the above results, it is presumed that the lubrication condition becomes worse in OA direction due to the increase in the contact area between the sheet and the die surface even during sheet hydroforming. It may also be considered that the change in the fluid-lubrication effect may be determined by the correlation between the thickening of the sheet and the film thickness of the pressure medium. This shows that the drawability can be

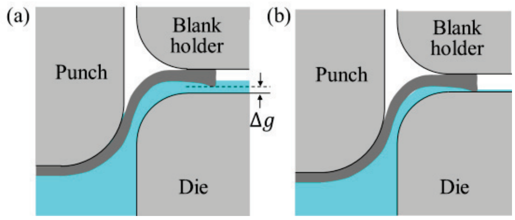

Fig. 5. Cross-sectional diagrams along OA direction. (a) Before the pump is terminated, and (b) after the pump is terminated.

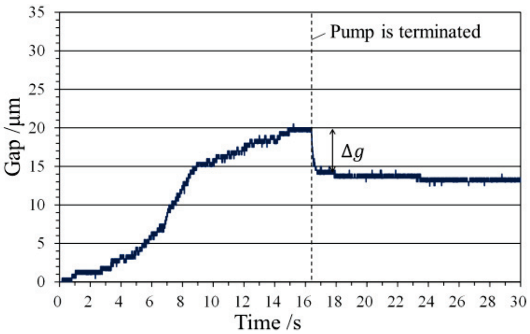

Fig. 6. Variation of gap during OB-opened condition with terminated punch stroke of 15mm.

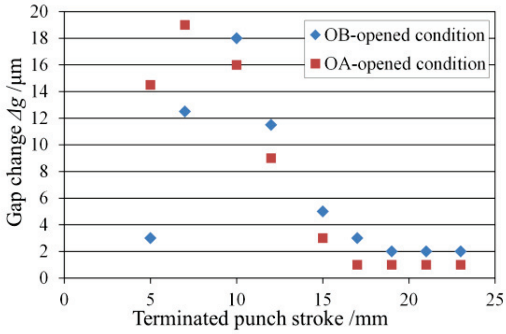

Fig. 7. Gap change between before and after the pump is stopped.

further improved by improving the lubrication condition in OA direction in the late stage of the process.

Moreover, the above results also indicate that there should be other factors that worsen the lubrication condition in OB-opened condition (Fig. 3). One of the factors can be explained as follows. As shown in Fig. 4, the thickening in OB direction is much smaller than that in OA direction, indicating that the lubrication condition in OB direction is better than that in OA direction. However, because the pressure medium is released in OB direction during OB-opened condition, the lubrication condition in OB direction becomes worse as well as that in OA direction; thus the overall lubrication condition on the die surface becomes worse in OB-opened condition than in OA-opened condition. This indicates that the lubrication condition may be different depending on the position of the die surface even during sheet hydroforming.

4. Conclusions

The variation of the lubrication condition on the die surface during sheet hydroforming was investigated experimentally. To examine the variation of the lubrication condition in the flange area, the pressure medium in the flange area was purposely released through holes made on the die surface. The following conclusions were drawn.

(1) The gap between the die and the blank holder is determined mainly by the film thickness of the pressure medium in the beginning of the process. On the other hand, it is governed by the thickness at the sheet edge in the lateral directions in the late stage of the process because of the pronounced thickening at this position.

(2) After the gap starts being determined mainly by the thickness, the lubrication condition would become worse because the contact area between the sheet and the die surface increases.

(3) The sheet fractures earlier when the pressure medium is released in the diagonal directions of the die surface, whereas the results remain almost unchanged when the pressure medium is released in the lateral directions. This shows that the lubrication condition is different depending on the position of the die surface even during the sheet hydroforming.

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